Response to Referees

Comments from Referee #2:

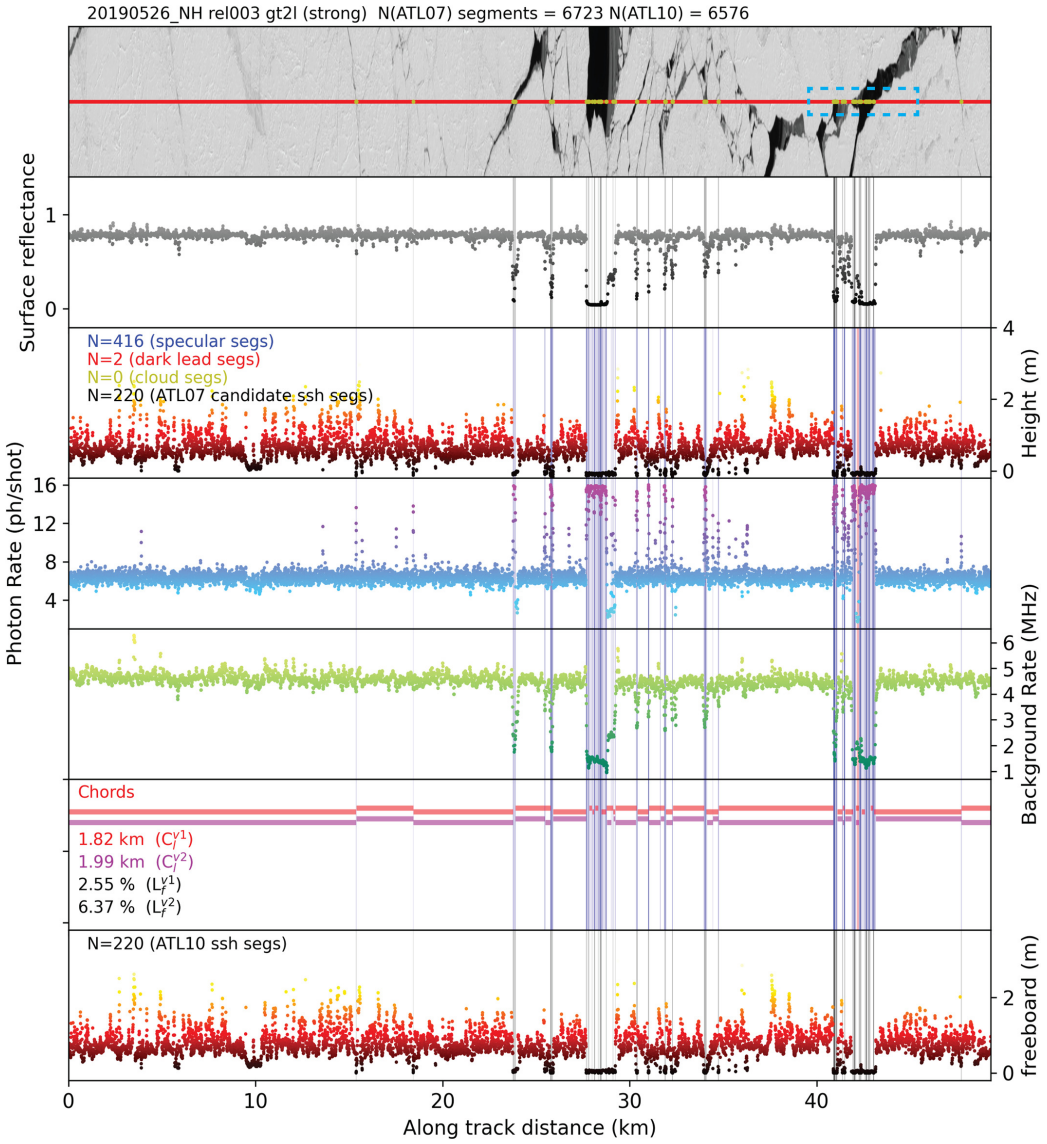
General Comments

In this manuscript, the authors map sea ice leads from ICESat-2 across the Arctic in winter from 2018 to 2024, using both ATL07 and ATL10. Interannual and regional variations in lead fraction, and differences between ATL07 and ATL10, are presented and discussed. The paper is well written and of interest to the community. I have some general comments to improve the depth of the analysis and discussion but recommend publication following these revisions.

We thank the referee for their constructive comments on our manuscript. We have carefully considered all feedback and have addressed each of them below, which we believe has improved the quality and clarity of our work. Line and figure numbers refer to the highlighted revised manuscript.

There are discrepancies between ATL07 and ATL10 regarding the magnitude of lead fraction; in Section 5 Line 246, the magnitude of ATL10 lead fraction is noted as ~5 times greater than in ATL07. The choice of freeboard threshold is interrogated in Section 5.2. which is useful, but I think further interrogation of ATL07 compared to ATL10 is important. The strict classification of specular leads in ATL07 reduces the number of leads detected, but how does this compare to where ATL10 detects leads? Are they detecting the same leads? Perhaps comparison to some imagery would be useful to understand where the differences are coming from.

The comparison between satellite imagery and ATL07/10 has been investigated by Petty et al. (2021, *Assessment of ICESat-2 Sea Ice Surface Classification with Sentinel-2 Imagery: Implications for Freeboard and New Estimates of Lead and Floe Geometry, doi: 10.1029/2020EA001491*), in which the authors compared ATL07/10 with the near-coincident Sentinel-2 satellite imagery. A case study over the Lincoln Sea of the Arctic Ocean on May 26, 2019, is presented in their Figure 3 (attached below). The purple lines and the yellow dots indicate where specular leads are identified by ATL07. Freeboard heights from ATL10 are shown on the bottom panel. All open-water leads shown on the top panel were successfully detected as specular leads by the ATL07 algorithm, including some freshly closed ones (along track distance ~16 km and ~18 km). Notably, features that appear to be closed for some time in the Sentinel-2 imagery (e.g., along track distance of ~6 km and ~10 km), are not identified as specular leads in ATL07, yet exhibit reduced freeboard heights in ATL10. Under certain criteria, these features could be potentially identified as leads using ATL10 data.



This case study provides evidence supporting the validity of ATL07/10 algorithms. Partly motivated by Petty et al. (2021), our work extends the analyses to all leads across the pan-Arctic over nearly the entire ICEat-2 sampling periods, as further discussed in Lines 91-94.

To address the referee's suggestion to expand the discussion of ATL07-10 discrepancy, we added a sentence in Line 258: "A detailed analysis of discrepancies is not feasible in the pan-Arctic. However, a previously published case study provides some evidence comparing ATL07/10 products with Senitel-2 imagery (Petty et al., 2021), which shows that ATL10 is capable of capturing leads that are closed for a longer time, beyond the open or freshly closed ones detected by ATL07."

In Section 4.1.1., and Figure 2, there are notable differences between ATL07 and ATL10 specifically over the Canadian Arctic Archipelago (CAA) and south of the New Siberian Islands. This is an interesting result which should be developed further; the difference is

briefly mentioned in Section 5 Lines 245-249, but there is not discussion about why these differences are present specifically in these regions, and what this means for interpreting the ATL07/ATL10 lead climatology and resultant sea surface height and freeboard in these areas.

The much larger lead fraction in ATL10 than ATL07 in these two regions implies that more non-specular leads are present, which are detected by ATL10 but not ATL07. This is consistent with our inference of larger average lead size in ATL10 as described in Lines 171-174, as larger ice leads are more prone to sea surface disturbances and thus reduces their specularity. In fact, relatively high sea surface height variability is indeed found in these two regions (from ICESat-2 ATL21 products), making the leads less smooth and less specular.

Following the referee's suggestion, we added a paragraph to the end of section 4.1.1 in Lines 178-181: "The larger average lead size in ATL10 compared to ATL07 in the Canadian Arctic Archipelago and the New Siberian Islands indicates the predominance of non-specular leads in these regions, as larger leads allow for the development of rougher sea surfaces with low specularity. This is consistent with the considerably higher lead fractions found in ATL10 than in ATL07 (Figure 3a-b)."

Specific Comments

Line 7 – I think a full stop would be better here, i.e. '…including a maximum in winter 2020-2021. Increases in lead fraction are primarily driven by changes in the number of larger (>100 m) leads.'

We have changed the text as suggested.

Line 23 – Could you include a reference for 'small leads comprise the majority of the lead area'?

We have added the reference to the mentioned sentence in Line 23.

Line 28 – I think it's important to clarify the different challenges for the different types of sensor, e.g., SAR vs thermal infrared imagery.

We added challenges in different types of sensors in the later part of this paragraph (Lines 31-36) that reads "In addition to the resolution and space constraints, each type of sensor also faces their own technical challenges translating raw measurements into reliable lead detections. For example, Synthetic Aperture Radar imagery is susceptible to the ambiguity of sea ice backscatter under different environmental conditions \citep[e.g.,][]{Zakhvatkina2019}, while thermal infrared retrievals require careful threshold selection of brightness temperature to discriminate leads from ice \citep[e.g.,][]{Qiu2023}.

Collectively, these resolution, coverage, and sensor-specific limitations highlight the need for a consistent, high-resolution, pan-Arctic lead characterization."

Table 1 – I find the layout of this table quite hard to read. Please resize the table to improve the formatting.

We have extended the widths of the table columns for better visualization.

Table 1 – Could you comment on how the different sea ice concentration filters in ATL07 and ATL10 may influence their lead detection? ATL10 will exclude areas with a lower ice concentration and presumably therefore exclude areas with a higher lead fraction.

This point was also brought up by referee #1. We added text in Line 60 to outline the influence of the different masks used in these two products, and the detection methods: "Methodological differences in lead detection between the two products contribute to the differences in both lead classification and total counts. The ice concentration filtering excludes portions of the ice edge where lead fractions are expected to be highest. As a result, leads near the ice edge are absent from both products, with ATL10 missing a larger portion due to its more restrictive filter."

Figure 1 – Please adjust the figure size so that less of the text in (a) is overlapping with the plot.

Figure 1 in the comment is Figure 2 in the highlighted manuscript (following a comment from referee #1 to add a flowchart). We have modified the figure as suggested (shown below), together with a comment from referee #1.

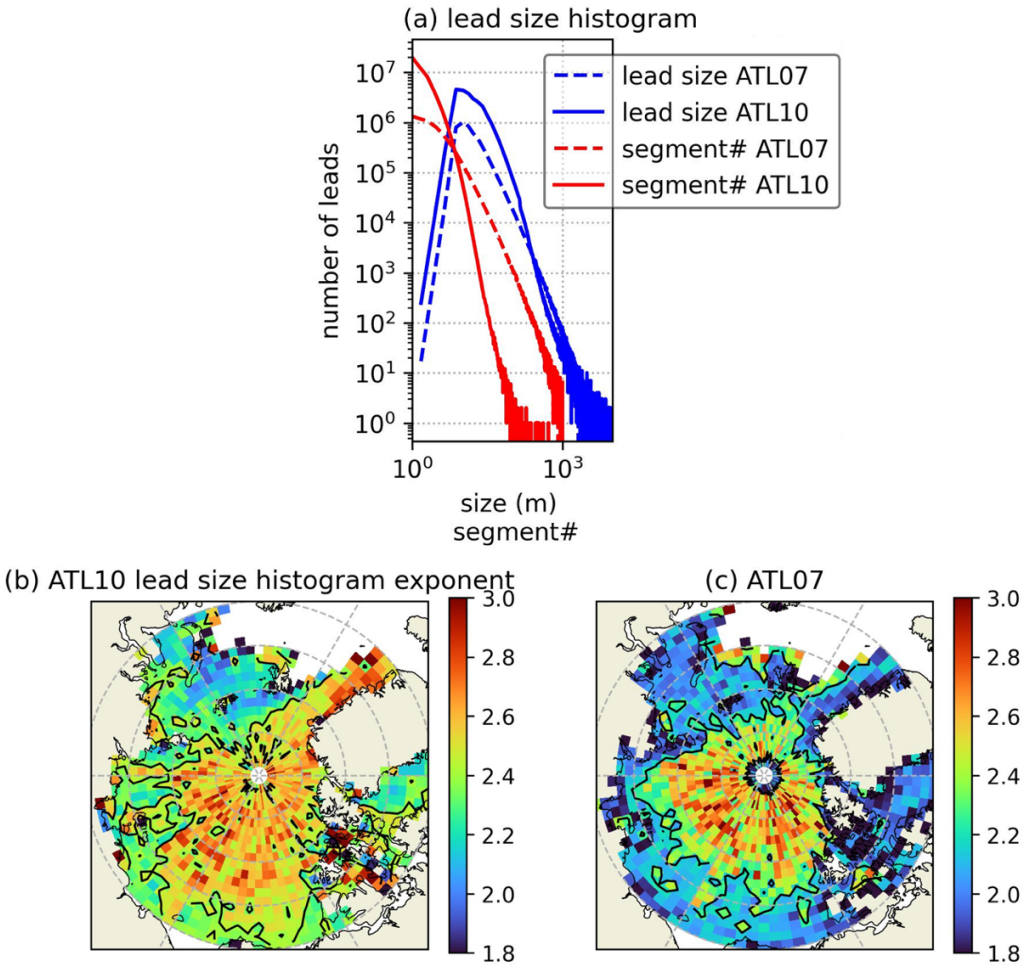


Figure 1 – Why does the number of segments increase towards the pole hole and then decrease again (but remain above zero)? This may just be my misunderstanding, but I would've expected the number of segments to increase with the increase in track density towards the pole, but then be zero above 88˚N.

Figure 1 in the comment is Figure 2 in the highlighted manuscript (following a comment from referee #1 to add a flowchart). ICESat-2 ground tracks are bounded by 88˚N. However, each ground track corresponds to 3 pairs of strong-weak beams of ~3.3 km apart, resulting in some measurements north of 88˚N. To clarify, we added "ICESat-2's ground track" in Line 54.

Section 3.2. – Does the lead fraction calculation require a minimum number of valid points? For example, cloud coverage could obscure the majority of a track in a grid cell, which would distort the resultant lead fraction.

We did not apply any minimum number criteria in our calculation of lead fraction. The sampling size of lead and ice segments is substantial, even on a grid cell (as shown in

Figure 2). The small standard errors (shown in Figure 6) also prove the statistical significance of our lead fraction calculation.

Figure 4, caption – I'm not sure I understand what is meant by 'only grid cells with the same signs in the two products are shown'.

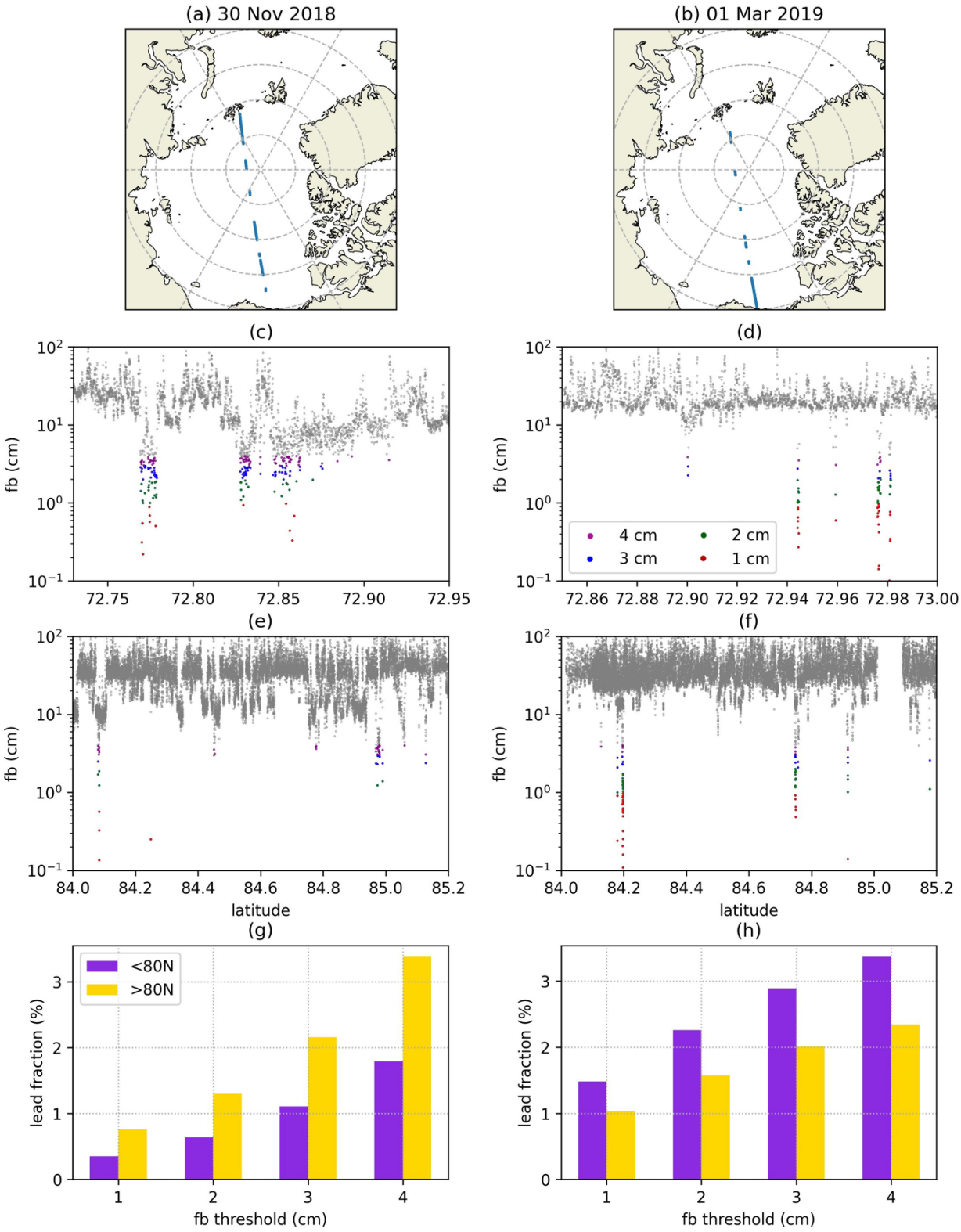
Figure 4 in the comment is Figure 5 in the highlighted manuscript, following a comment from referee #1 to add a flowchart. The color represents the lead fraction anomaly relative to their climatology. Only grid cells where the lead fraction anomaly derived from ATL07 and ATL10 have the same signs are shown. This is to highlight the common features between the two products. To clarify, we changed the last sentence of the caption to "Only grid cells with the same signs in lead fraction anomaly derived from the two products are shown, highlighting features that are consistent between the two products."

Figures 5 and 6 – I don't think that Archipelago should be the plural 'Archipelagos' here, assuming it is only referring to the Canadian Arctic Archipelago? Perhaps it would be useful to use the CAA acronym on the Figures.

Figure 5 (6) in the comment is Figure 6 (7) in the highlighted manuscript following a comment from referee #1 to add a flowchart. We have updated "Archipelagos" to "CAA" and updated the Figures, together with a comment about Figure 7 from referee #1.

Figure 7. Please increase the size of the points in the legend in (d), it is very difficult to make out the colors.

Figure 7 in the comment is Figure 8 in the highlighted manuscript following a comment from referee #1 to add a flowchart. We have increased the point size in the legend as suggested (shown below).


(a) 30 Nov 2018
(b) 01 Mar 2019
(c)
(d)
(e)
(f)
(g)
(h)
fb (cm)
latitude
4 cm
3 cm
2 cm
1 cm
<80N
>80N
lead fraction (%)
fb threshold (cm)

Line 277 – I think this paragraph could be further developed. What do MODIS, Envisat, and CryoSat-2 show in these studies? Are the spatial patterns/magnitudes of lead fraction consistent? There is also a more recent MODIS climatology, from:

Willmes et al. (2023). Patterns of Arctic sea-ice leads and their relation to winds and ocean currents. The Cryosphere, 17, 3291-3308, DOI:10.5194/tc-17-3291-2023.

We thank the referee for the suggested reference, and we have added this reference to texts describing MODIS-related work. We added more detail to previous work to this paragraph in Lines 297-299: For example, lead frequency, the ratio of lead counts over the total number of counts per pixel and month/year, is used to characterize sea ice occurrence in MODIS \citep{Willmes2015,Willmes2023}, while the percentage of lead waveforms are used in Envisat and CryoSat-2 work \citep{Tilling2019}.

Grammatical Comments

We have made the language-related changes according to the following suggestions.

Line 26 – CryoSat-2
Line 89 – selected to be a sea surface
Line 122 – problems
Line 152 – the smallest ratio is present near the ice edge… opposite to the lead fraction
Line 153 – potential reasons
Line 160 – south of the New Siberian Islands
Line 162 – the total number of leads
Line 163 – lead numbers in both products
Line 164 – similar conclusions can be drawn
Line 235 – more large leads
Line 276 – consistent

Please check for consistency in capitalizing regions, e.g., Section 4.2.1. and Figure 6 ‘Central Arctic’ versus ‘central Arctic’.

Figure 6 in the comment is Figure 7 in the highlighted manuscript following a comment from referee #1 to add a flowchart. We have updated the texts and figures to use “Central Arctic” consistently.